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Review article

Mushroom oils: A review of their production, composition, and potential applications

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ABSTRACT

This review delves into the world of mushroom oils, highlighting their production, composition, and versatile applications. Despite mushrooms' overall low lipid content, their fatty acid composition, rich in essential fatty acids like linoleic acid and oleic acid, proves nutritionally significant. Variations in fatty acid profiles across mushroom species and the prevalence of unsaturated fats contribute to their cardiovascular health benefits. The exploration extends to mushroom essential oils, revealing diverse volatile compounds through extraction methods like hydrodistillation and solvent-assisted flavor evaporation (SAFE). The identification of 1-octen-3-ol as a key contributor to the distinct "mushroom flavor" adds a nuanced perspective. The focus broadens to applications, encompassing culinary and industrial uses with techniques like cold pressing and supercritical fluid extraction (SFE). Mushroom oils, with their unique nutritional and flavor profiles, enhance gastronomic experiences. Non-food applications in cosmetics and biofuels underscore the oils' versatility. The nutritional composition, enriched with essential fatty acids, bioactive compositions, and trace elements, is explored for potential health benefits. Bioactive compounds such as phenolic compounds and terpenes contribute to antioxidant and anti-inflammatory properties, positioning mushroom oils as nutritional powerhouses. In short, this concise review synthesizes the intricate world of mushroom oils, emphasizing their nutritional significance, extraction methodologies, and potential health benefits. The comprehensive overview underscores mushroom oils as a promising area for further exploration and utilization. The characteristics of mushroom biomass oil for the use in various industries are influenced by the mushroom species, chemical composition, biochemical synthesis of mushroom, and downstream processes including extraction, purification and characterization. Therefore, further research and exploration need to be done to achieve a circular bioeconomy with the integration of SDGs, waste

Abbreviations: PUFA, polyunsaturated fatty acid; MUFA, mono-unsaturated fatty acid; SFA, saturated fatty acid; SSF, solid state fermentation; SLF, submerged liquid fermentation; SAFE, solvent-assisted flavor evaporation; HDL, high density lipoprotein; LDL, low density lipoprotein; SFE, supercritical fluid extraction; GC, gas chromatography; MS, mass spectrometry.

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reduction, and economic stimulation, to fully utilize the benefits of mushroom, a valuable gift of nature.

1. Introduction

The exploration of mushroom oils has evolved into a captivating field of study, drawing increasing attention due to their diverse applications in nutrition, health, and various industries. This review aims to delve into the multifaceted aspects of mushroom oils, offering insights into their production processes, intricate chemical composition, and the expansive spectrum of potential applications. Mushrooms, a staple in culinary traditions worldwide, have long been valued not only for their rich flavors but also for their potential health benefits [1,2]. The extraction of oils from these fungal organisms has emerged as a novel avenue, opening up a realm of possibilities for researchers, culinary experts, and health enthusiasts alike.

The production of mushroom oils is a complex process influenced by various factors, such as the choice of extraction methods and the specific mushroom species involved. Hydrodistillation, a traditional method, employs steam to extract essential oils from mushroom biomass, preserving volatile compounds that contribute to the distinctive aroma and potential therapeutic properties. In contrast, solvent-assisted techniques, including methods like solvent-assisted flavor evaporation (SAFE), provide a more tailored approach, allowing for the selective extraction of specific components [3]. This diversity in production methods significantly influence the chemical profile of mushroom oils, shaping their unique characteristics and potential applications [4].

At the core of understanding mushroom oils lies an exploration of their chemical composition. These oils are a rich source of essential fatty acids, such as linoleic acid and linolenic acid, contributing to their nutritional value. Furthermore, the presence of terpenes and phenolics contribute to mushroom oils distinctive flavors and potential bioactive properties. Some mushroom species even produce special fatty acids like ergosterol fatty acids, adding an intriguing layer to their chemical complexity. A detailed analysis of these constituents forms the foundation for unravelling the therapeutic potential and culinary versatility of mushroom oils [5,6].

The potential applications of mushroom oils are expansive and extend far beyond the culinary domain. In the kitchen, these oils can serve as flavor enhancers, imparting a unique mushroom essence to various dishes [1,2]. However, their significance transcends gastronomy, as the bioactive compounds present in mushroom oils have been linked to a range of health benefits. Antimicrobial, antioxidant, anti-inflammatory, and anticancer properties have been reported, positioning mushroom oils as valuable ingredients in the development of nutraceuticals and dietary supplements [7,8].

This review will navigate through the vast array of mushroom species recognized for their oil content, exploring how factors such as growth conditions, extraction techniques, and geographical variations influence the chemical composition of these oils. Additionally, it will shed light on the potential of mushroom oils as sustainable sources of biofuels, contributing to the broader discourse on environmentally conscious practices. Amidst the exploration of the vast potential of mushroom oils, it is imperative to scrutinize the quality and safety aspects governing their production and consumption. Robust analytical techniques and stringent quality control measures are indispensable to ensure the consistency, purity, and safety of mushroom oils across diverse applications [9].

In essence, this review aspires to serve as a comprehensive guide to mushroom oils, weaving together their production intricacies, chemical nuances, and the far-reaching applications that span culinary delights, health and wellness, and sustainable practices. Through this exploration, we aim to contribute to the growing body of knowledge surrounding mushroom oils, fostering a deeper understanding of their impact on human well-being and the broader spectrum of industries they touch.

Mushroom, a macrofungal that has typical physical appearance with an umbrella-like structure known as pileus (cap), a stem-like structure called stipe (stem) and a root-like structure which is the sclerotium (root). This type of fungus is classified under the phylum of basidiomycota in which sporulation will occur during reproduction. Due to their distinctive flavors and textures, the basidiomycetes have been reported to serve as condiments that enhance the flavor of food for centuries. Besides being used as food flavoring, mushrooms are also well-known by its medicinal and functional importance [1,2]. Since they are nutritious and delicious, very often they form popular dietary components because of their richness in protein, fiber, vitamins B, vitamin D, antioxidants, and minerals like potassium, selenium. There are medicinal as well as culinary-medicinal mushrooms. Some species of basidiomycetes are renown worldwide, for instance, shiitake mushroom (*Lentinula edodes*), maitake mushroom (*Grifola frondosa*), button mushroom (*Agaricus* sp.), Jew's ear fungus (*Auricularia auricularis*), oyster mushroom (*Pleurotus ostreatus*), turkey tail mushroom or Yunzhi (*Coriolus versicolor*), caterpillar fungus (*Cordyceps* sp.), and reishi mushroom or Lingzhi (*Ganoderma* sp.). One of the most impressive characteristics shown in mushrooms is that the intake of mushroom or mushroom-derived products will trigger series of bioactivities which improve human health such as anti-cancer, immuno-stimulating, anti-hyperglycemic, anti-hypertensive, neuroprotective, hepato-protective, anti--fungal, antibacterial, prebiotic and antiviral properties [7,8].

Nowadays, the post-harvest quality had become the major concern among mushroom-growers. Although edible basidiomycetes are a highly perishable commodity, but there are some limitations still required to be resolved such as the long-term storage and long-distance transportation of mushrooms. Even though several methods have been developed to enhance the post-harvest shelf-life of mushrooms, but only a few had successfully achieved. The use of essential oils in the storage of mushrooms is a relatively new concept, but had shown positive results in improving the quality attributes of harvested fruiting bodies of the basidiomycetes [4].

With the appreciation to the advancement of biotechnology, the production mushroom is no longer dependent only with the harvesting of mushroom fruiting bodies from mushroom farms or nurseries. The production of mushroom biomass can be achieved by cultivating the fungal mycelium in both solid and liquid media via solid state fermentation (SSF) and submerged liquid fermentation (SLF) respectively [10–13].

Table 1
Fatty acid composition in different mushroom species (% dry weight).

Sources	SFA				MUFA			PUFA		Reference
	Myristic acid (C14:0)	Palmitic acid (C16:0)	Stearic acid (C18:0)	Arachidic acid (C20:0)	Palmitoleic acid (C16:1)	Oleic acid (C18:1 n-9)	Eicosenoic acid (C20:1 n-9)	Linoleic acid (C18:2 n-6)	α-linolenic acid (C18:3 n-3)	
Agaricus arvensis	2.34	14.55	3.37	0.87	4.32	15.46	0.07	56.11	0.19	Barros, Baptista [17]
Agaricus bisporus	0.58	14.02	6.54	3.16	0.42	20.58	0.8	43.87	3.25	Sande, de Oliveira [16]
Boletus edulis	–	–	–	–	–	8.2	–	75.6	0.5	Ayaz, Chuang [20]
Boletus reticulatus	0.37	11.26	5.84	0.58	0.75	37.61	0.50	36.60	–	Günç Ergönül, Akata [18]
Coprinus comatus	–	–	–	–	–	5.7	–	71.1	1.1	Cohen, Cohen [21]
Flammulina velutipes	–	–	–	–	–	10.7	–	51.2	13.0	Cohen, Cohen [21]
Flammulina velutipes	0.50	14.56	3.56	0.19	0.70	16.37	0.08	40.87	0.01	Günç Ergönül, Akata [18]
Ganoderma lucidum	0.24	21.3	5.94	0.56	5.83	60.1	0.61	3.00	–	Salvatore, Elvetico [22]
Lactarius deliciosus	0.48	12.08	25.33	0.44	0.92	41.26	0.10	17.06	0.26	Barros, Baptista [17]
Lactarius salmonicolor	0.16	7.76	7.27	0.45	0.22	18.98	0.03	59.44	–	Günç Ergönül, Akata [18]
Leucopaxillus giganteus	2.70	13.46	2.11	0.12	12.91	21.09	0.07	46.18	0.09	Barros, Baptista [17]
Lignosus rhinocerotis	–	2.37	–	–	–	–	–	45.35	–	Nallathamby, Lakshmanan [23]
Pleurotus ostreatus	–	–	–	–	–	10.4	–	65.29	0.0	Günç Ergönül, Akata [18]
Pleurotus ostreatus	0.66	12.40	3.71	0.13	0.46	10.36	0.11	65.29	0.03	Günç Ergönül, Akata [18]
Pleurotus sajor-caju	–	–	–	–	–	22.6	–	48.6	0.2	Obodai, Ferreira [24]
Polyporus squamosus	0.58	17.21	3.28	0.30	0.65	33.02	0.11	38.91	0.27	Günç Ergönül, Akata [18]
Russula anthracina	0.15	9.16	12.96	0.21	0.64	52.11	0.18	22.39	0.01	Günç Ergönül, Akata [18]
Sarcodon imbricatus	0.27	11.14	3.65	0.88	0.98	45.06	0.15	35.38	0.16	Barros, Baptista [17]
Tricholoma portentosum	0.13	5.60	2.33	0.13	0.51	58.36	0.15	30.88	0.40	Barros, Baptista [17]

In the year of 2019, the world mushroom cultivation had achieved at approximately 11.9 million tonnes per year, with the People's Republic of China being the largest mushroom producer (8.9 million tonnes), followed by Japan (0.47 million tons) and the United States of America (0.38 million tonnes). This cultivation trend is expected to continue growing in the future [14]. This is a great scenario in which the mass production of mushroom biomass through different techniques will result in more research and development works on the chemicals to be extracted from the cultivated mushroom biomass that will contribute to the economy due to their importance in various fields such as nutrition, pharmaceutical, cosmeceutical, medicinal as well as bioenergy [15]. The products of interest vary with the fungal strains, therefore, in most studies, there are only a few bioactive compounds were being extracted from the mushroom biomass for research purposes. Yet, there are more to be discovered with thousands of mushroom species available in the world.

2. Types of fatty acids from mushroom biomass

Fatty acids are naturally existed in the mixed form of saturated (SFAs), mono-unsaturated (MUFAs), and polyunsaturated fatty acids (PUFAs) in mushroom. Some essential fatty acids such as oleic acid, linoleic acid and stearic acid make up a significant portion in the lipid composition of mushroom in several instances despite mushroom being reported to have an overall low lipid content. The average percentage of lipid content in edible mushroom biomass of different species is 4.0 % (dry weight), ranging from 1.1 to 8.3 % (dry weight). Unsaturated fatty acids were reported to present in larger proportions in mushroom fatty acid composition than saturated fatty acids in numerous studies [16–19]. Table 1 summarizes the fatty acid composition of different mushroom species.

Linoleic acid (C18:2, $\Delta^{9,12}$), an essential polyunsaturated fatty acid (PUFA) which was reported as the predominant fatty acid species which make up the lipid profile of most of the studied mushroom species. In a study of five wild edible mushroom from Northeast Portugal, linoleic acid was the fatty acid which showed the greatest abundance among other fatty acids in the lipid composition [17]. The percentages of linoleic acid ranged from 17.06 % to 56.11 % in five different edible mushroom species. Among the sample species, only *Lactarius deliciosus* showed relatively low linoleic acid level (17.06 %), while in the other four mushroom species (*Agaricus arvensis, Leucopaxillus giganteus, Sarcodon imbricatus, Tricholoma portentosum*), linoleic acid was found to be the predominant fatty acid in the lipid composition [17]. Similar findings were reported in another study on analysing the fatty acid composition of six different wild edible mushroom species (*Boletus reticulatus, Flammulina velutipes* var. *velutipes, Lactarius salmonicolor, Pleurotus ostreatus, Polyporus squamosus,* and *Russula anthracina*) in from Anatolia where all selected species were reported to have *cis*-linoleic acid contributing to the highest portion in the fatty acid composition, which varied from 22.39 % to 65.29 % [18]. Majority of the literatures reveal that PUFAs including linoleic acid, α-linolenic acid, γ-linolenic acid, were the major fatty acids in being extracted from mushroom biomass, with linoleic acid being the most abundant PUFA and this evidence suggested that linoleic acid plays a crucial role in mushroom metabolism, in which the level of fatty acid will be affected based on the growth conditions, substrate, and other environmental factors [16–18,20–24].

It is crucial to note that fatty acid composition varies among mushroom species. Linoleic acid had been outlined in prior studies on its predominance in the fatty acid profile of mushroom species, as the most common PUFA which can be found in mushroom. Among the major mushroom biomass fatty acids, oleic acid (C18:1, Δ^{9}) was found to be the most common mono-unsaturated fatty acid (MUFA) in the lipid profile of mushroom species. According to the findings demonstrated by Barros, Baptista [17], the percentages of oleic acid were higher than linoleic acid in *Lactarius deliciosus*, *Sarcodon imbricatus*, and *Tricholoma portentosum*, with the oleic acid to linoleic acid percentage ratio (%: %) of 41.26 : 17.06, 45.06 : 35.38, and 58.36 : 30.88, respectively [17]. Another study from Italy revealed that oleic acid was the predominant species of fatty acid in the fatty acid composition of *Ganoderma lucidum* with a remarkably high percentage of 60.1 %–68.4 %, obtained by performing different extraction techniques [22]. It had been observed that oleic acid was the main fatty acid with the greatest percentage in the biomass of *Russula anthracina* (52.11 %) in the fatty acid composition analysis [18]. In addition to oleic acid, there were different MUFA being reported as the constituents of the fatty acid composition of mushroom species, such as, palmitoleic acid, eicosenoic acid, myristoleic acid, pentadecanoic acid, heptadecenoic acid, erucic acid, and nervonic acid, however, the level of these fatty acids are comparatively low to oleic acid level in the majority of the studied mushroom species [16–18,20–24].

As aforementioned, the fungal lipid profile contains a mixture of unsaturated fatty acids and saturated fatty acids (SFAs). Based on the literature, the findings have been presented to show that palmitic acid (C16:0) and stearic acid (C18:0) were commonly being reported in the fatty acid composition analysis of the extract from mushroom biomass [16–18,20–24]. From the literatures studying 17 edible mushroom species, generally, the percentage of palmitic acid is higher than stearic acid, ranging from 2.37 % to 21.3 %. *Lactarius deliciosus* was the only mushroom species being studied which showed higher stearic acid level (25.33 %) than palmitic acid (12.08 %) [17]. Other SFA's contribution to the fatty acid composition of mushroom, such as myristic acid, arachidic acid, margaric acid, behenic acid, and lignoceric acid, though present in insignificant amount, these SFAs also have their importance in mushroom metabolism, especially as the precursors of the unsaturated fatty acids [16–18,20–24].

Mushrooms are indeed known for having relatively low total fat content, and the fat they contain are often of the unsaturated variety, which includes MUFAs and PUFAs [19]. The reason for the lower SFA content in mushrooms can be attributed to their biological makeup and the fact that they are not significant sources of animal fats [25,26]. Instead, mushrooms tend to contain higher proportions of healthier unsaturated fats, such as linoleic acid (an omega-6 fatty acid) and linolenic acid (an omega-3 fatty acid). These unsaturated fats are associated with various health benefits, including cardiovascular health [19,27].

3. Essential oils from mushroom biomass

Essential oils have long been recognized for their numerous therapeutic and aromatic properties, predominantly sourced from plant materials [28]. However, recent research has unveiled a novel and promising source of essential oils – mushroom biomass. Researchers are working on this topic, exploring the extraction methods, chemical composition, and potential applications of essential oils derived from mushroom biomass [1,29]. The unique chemical profiles and biological activities of these oils make them a subject of growing interest in various fields, including pharmaceuticals, cosmetics, and food industries [30].

3.1. Extraction method of essential oils from mushroom biomass

The extraction of essential oils from mushroom biomass involves several methods, each with its advantages and limitations. Common techniques include steam distillation, hydrodistillation, solvent extraction, solvent-assisted flavor evaporation (SAFE) and supercritical fluid extraction (SFE). Researchers are actively exploring innovative methods to optimize the extraction process, improve yield, and preserve the integrity of the extracted oils. Studies have demonstrated that hydrodistillation and solvent-assisted flavor evaporation (SAFE) were the two commonly employed extraction techniques by researchers to achieve better essential oil yield as well as preserving the quality of mushroom essential oil [1,3,28–30].

Hydrodistillation is a method of essential oil extraction that involves the use of water and heat to capture the volatile compounds present in sample materials [3,31]. This technique is commonly employed for extracting essential oils from various botanical sources, including herbs, flowers, seeds, and mushroom. Hydrodistillation is a traditional and widely used method with a history dating back centuries, which involves heating of mixture of water and sample materials, vaporisation of essential oil, condensation of vaporised mixture, separation of essential oil from water (condensate), and collection of essential oil [3,31]. Hydrodistillation is known for its simplicity and cost-effectiveness. However, it may not be the most efficient method for extracting essential oils from certain materials, especially those with heat-sensitive compounds. In such cases, other methods like steam distillation or cold-press extraction might be preferred. The choice of extraction method depends on the type of sample material and the desired composition of the extracted essential oil [1–3].

Solvent-assisted Flavor Evaporation (SAFE) is a technique used for the isolation and concentration of volatile compounds, particularly flavor and aroma compounds, from complex matrices such as food, beverages, and natural products [32]. It is a specialized extraction method that combines the principles of solvent extraction and evaporation to obtain concentrated flavor and fragrance extracts. SAFE process is more sophisticated than hydrodistillation as the sample is typically mixed with a suitable solvent which will help to dissolve and extract the volatile compounds from the sample matrix [1–3,32]. The mixture will then be subjected to extraction process, evaporation of solvent for concentrating the volatile components, condensation, and collection of the extracts, and finally being analyzed using various analytical techniques such as gas chromatography (GC) or mass spectrometry (MS), to identify and quantify the specific compounds responsible for the flavor and aroma characteristics. SAFE has several advantages, including its ability to extract a wide range of volatile compounds, including both polar and non-polar substances. It also allows for the concentration of these compounds, making it easier to analyse and characterise complex flavor profiles. Additionally, SAFE is known for its versatility

Table 2
The chemical constituents of the essential oils derived from mushroom biomass via different extraction techniques.

Fungal species	Extraction method	Characterization method	Main Constituents	Percentage (%)	Reference
P. salmoneostramineus	HD[a]	GC-MS[b]	1-octen-3-ol	12.5	Usami, Nakaya [3]
			Hexadecenoic acid	11.5	
			Linoleic acid	9.9	
P. salmoneostramineus	SAFE[c]	GC-MS	11-(1-ethylpropyl)-heneicosane	12.9	Usami, Nakaya [3]
			1-octen-3-ol	11.3	
			2-butoxyethanol	11.0	
P. sajor-caju	HD	GC-MS	Ethyl linoleate	36.9	Usami, Nakaya [3]
			Hexadecanoic acid	23.4	
			Diphenylolpropane	9.0	
P. sajor-caju	SAFE	GC-MS	Methional	27.6	Usami, Nakaya [3]
			6-undecanone	23.2	
			Dimethyl sulfone	10.2	
S. verrucosum	HD	GC-MS, HP-5 column[d]	3-octanone	49.1	Yayli, Yilmaz [34]
			3-octanol	26.8	
C. infractus	HD	GC-MS, HP-5 column	Musk ambrette	62.3	Yayli, Yilmaz [34]
			DL-limonene	5.5	
H. capnoides	HD	GC-MS, HP-5 column	1-octen-3-ol	21.7	Yayli, Yilmaz [34]
			3-octanol	14.3	
H. fasciculare	HD	GC-MS, HP-5 column	1-octen-3-ol	18.2	Yayli, Yilmaz [34]
			DL-limonene	14.2	

[a] Hydrodistillation.
[b] Gas Chromatography – Mass Spectrometry.
[c] Solvent-assisted Flavor Evaopration
[d] High Performance Liquid Chromatography (5 capillary column).

and can be applied to various sample types. However, it is essential to note that the choice of solvent, extraction conditions, and other parameters can influence the efficiency and selectivity of the SAFE process [1,3,28–30,32]. Researchers and flavor scientists often tailor the method to suit the specific requirements of the samples being analyzed. According to the literatures, the yield of essential oils varied with the type of extraction technique being employed. hydrodistillation had been observed to show higher efficiency in obtaining the essential oils from mushroom biomass as compared to SAFE method in terms of oil yield. Additionally, the chemical composition of the essential oils extracted were reported to have some differences when different extraction techniques were applied. The essential oils obtained from *Pleurotus salmoneostramineus* and *Pleurotus sajo-caju* via HD and SAFE method showed different chemical compositions as demonstrated by Usami, Nakaya [3].

3.2. Chemical compositions and properties of mushroom essential oils

Mushroom essential oils exhibit a wide array of volatile compounds, including terpenes, sesquiterpenes, aliphatic compounds, and oxygenated monoterpenes. The composition varies not only between mushroom species but also within different parts of the same mushroom. The intricate chemical makeup contributes to the unique aromas and potential therapeutic properties of these oils. The literatures reveal that the unsaturated varieties of alcohols, carboxylic acids, and ketones were the main constituents being detected in the essential oil extracted from the biomass of edible mushroom. Among all the volatile compounds in the mushroom essential oil, 1-octen-3-ol are one of the most reported main mushroom essential oil constituents, which is suggested to be responsible for the "mushroom flavor" [1–3].

Evidence suggests that with different extraction procedures, different dominant volatile compounds would be detected even though the essential oil was from the same fungal species. For instance, in the study conducted by Usami, Nakaya [3], the predominant chemical constituents of essential oil extracted from *Pleurotus salmoneostramineus* through hydrodistillation and SAFE were

Table 3
The aromatic characteristics and chemical compositions of different mushroom oil.

Fungal species	Extraction method	Treatment/pre-treatment	Odour/flavor	Chemical composition	Reference
Pleurotus eryngii var. *ferulae*	HD[a]	Diethyl ether	Mushroom Potato Floral	1-octen-3-ol Methional Phenylacetaldehyde	Usami, Ono [2]
Pleurotus eryngii var. *ferulae*	HD	Dichloromethane	Mushroom Potato Sweet Floral	1-octen-3-ol Methional 3-octanone Phenylacetaldehyde	Usami, Ono [2]
Pleurotus eryngii var. *ferulae*	SAFE[b]	Diethyl ether	Mushroom Sweet	1-octen-3-ol 3-octanone Acetophenone	Usami, Ono [2]
Pleurotus eryngii var. *ferulae*	SAFE	Dichloromethane	Mushroom Floral Sweet	1-octen-3-ol Phenylacetaldehyde 2,3-butanediol	Usami, Ono [2]
Pleurotus eryngii var. *tuoliensis*	HD	Diethyl ether	Mushroom Potato Sweet	1-octen-3-ol Methional Nonanal	Usami, Motooka [1]
Pleurotus cystidiosus	HD	Diethyl ether	Garlic Mushroom Almond Burnt	Dimethyl trisulfide 1-octen-3-ol Acetophenone (*Z*)-α-bisabolene	Usami, Motooka [1]
Pleurotus salmoneostramineus	HD	Diethyl ether	Mushroom Sweet	1-octen-3-ol 3-octanone 3-octanol 2-pentylfuran	Usami, Nakaya [3]
Pleurotus salmoneostramineus	SAFE	Dichloromethane	Mushroom Green Sweet	1-octen-3-ol 3-octanol 3-octanone Hexanol 2-butoxyethanol	Usami, Nakaya [3]
Pleurotus sajor-caju	HD	Diethyl ether	Potato Mushroom Fruit	Methional 1-octen-3-ol Octanal	Usami, Nakaya [3]
Pleurotus sajor-caju	SAFE	Dichloromethane	Potato Sweet Green	Methional Benzaldehyde 2-ethylhexanol	Usami, Nakaya [3]
Morchella importuna	LE[c]	Fresh sample	Fruit Floral & honey-like Mushroom	3-methylbutanol Benzene acetaldehyde 1-octen-3-ol	Tu, Tang [40]

[a] Hydrodistillation.
[b] Solvent-assisted Flavor Evaporation.
[c] Lipophilic extract extraction.

1-octen-3-ol (12.5 %), hexadecenoic acid (11.5 %), linoleic acid (9.9 %); and 11-(1-ethylpropyl)-heneicosane (12.9 %), followed by 1-octen-3-ol (11.3 %) and 2-butoxyethanol (11.0 %), respectively. Similar findings were documented for hydrodistillated oil and SAFE-extracted oil of *Pleurotus sajo-caju*, showing different chemical compositions when different extraction techniques were employed. The chemical constituents of essential oils derived from mushroom biomass of different species via different extraction techniques is illustrated in Table 2.

In short, mushroom essential oils represent a burgeoning field of research with immense potential for diverse applications [1–3,30]. Their unique chemical composition, coupled with a broad spectrum of biological activities, positions them as valuable resources in the realms of health, beauty, and gastronomy. Continued exploration and understanding of mushroom essential oils are critical for harnessing their full potential and integrating them into various industries [30,33].

4. Characteristics of oils

Oils are integral components of the human diet and industrial processes, serving diverse purposes in cooking, nutrition, and manufacturing [35]. This section explores the production, characteristics, and evaluation of both food and non-food oils, highlighting their importance and versatility [35–38].

Food oils are predominantly derived from plant and animal sources. Common plant-based oils include olive oil, sunflower oil, and palm oil, while animal-based oils such as fish oil also contribute to culinary applications [36]. This section provides insights into the extraction methods, refining processes, and sustainability considerations associated with the production of food oils [36,39]. The chemical composition and physical properties of food oils significantly influence their functionality and nutritional value. Fatty acid profiles, antioxidants, and sensory attributes contribute to the unique characteristics of each oil.

Non-food oils find application in various industries, including cosmetics, pharmaceuticals, and biofuels [37,38]. Sources such as castor beans, jojoba seeds, and linseed contribute to the production of oils with specialized properties. This section explores the extraction methods and unique characteristics of non-food oils. Non-food oils possess distinct features that make them suitable for specific industrial applications. Viscosity, stability, and bioactive compounds are crucial factors influencing the performance of non-food oils in various non-edible contexts.

4.1. The use of mushroom biomass as a source of oil in food and non-food sectors

Edible oils have long been essential in culinary practices, and the recent discovery of mushroom-derived oils introduces an innovative dimension to this culinary landscape [36]. The extraction of edible oil from mushrooms involves specialized processes to capture the lipid content within the fungal biomass. Techniques such as cold pressing, solvent extraction, and supercritical fluid extraction are explored for their efficiency and impact on the quality of the extracted oil [36,39]. Mushroom-derived edible oils exhibit a unique nutritional profile, often characterized by a balance of essential fatty acids, antioxidants, and other bioactive compounds [8]. Additionally, the distinctive flavor profiles of mushroom-derived edible oils add a gourmet dimension to culinary creations. Whether subtly earthy, nutty, or possessing umami undertones, the flavors contribute to the overall sensory experience of dishes [1–3]. The aromatic attributes of different edible mushrooms are tabulated in Table 3. There are studies suggesting that the diversity in flavor profiles across different mushroom species could have potential applications in gastronomy [1,29]. Also, the versatility of mushroom-derived edible oils makes them attractive ingredients in various culinary applications. From salad dressings to sautés and marinades, these oils lend a unique character to dishes while potentially providing nutritional benefits. Due to mushroom's rich chemical profile, and its unique flavor attributes, there are discussions on the expanding role of mushroom-derived oils in contemporary cuisines [1–3,8].

While edible oils have long been a staple, the focus on non-food oil derived from mushrooms presents a new avenue for innovation [41]. The exploration of non-food oil derived from mushrooms has emerged as a ground-breaking area of research, offering novel solutions for various industrial applications. The extraction of non-food oil from mushrooms involves specialized techniques tailored to the unique lipid content of fungal biomass. Methods such as solvent extraction, cold pressing, and supercritical fluid extraction are explored for their efficiency and impact on the quality of the extracted oil [36,39]. Based on literature, the chemical composition of non-food oils derived from mushrooms unveils a spectrum of compounds with potential industrial applications. Fatty acids, sterols, and other bioactive constituents contribute to the distinctive properties of these oils [8]. The wide variety of chemical compositions of across various mushroom species has recently become a focus in the research field on emphasizing their potential advantages in non-food applications. This is mainly due to the unique properties exhibited by mushroom-derived non-food oils, including viscosity, stability, and compatibility with other ingredients, which make them desirable for specific industrial uses, especially in making them valuable in formulations for cosmetics, biofuels, and more.

In the cosmetic industry, there is an increasing interest in mushroom-based non-food oils due to their potential skincare benefits [42,43]. Antioxidant, anti-ageing, anti-wrinkle, skin whitening, moisturizing effects, and unique textures contribute to their appeal in formulations for creams, lotions, and other skincare products. In cosmeceuticals and nutricosmetics, the extracts of a wide range of fungal species which are presently used, or patented to be used as ingredients incorporated in creams, lotions, ointments, serums, and tonics, including *Lentinula edodes, Grifola frondosa, Ganoderma lucidum, Wolfiporia extensa, Cordyceps sinensis, Sparassis latifolia, Tremella* spp., *Agaricus bisporus, Pleurotus ostreatus, Hypsizygus ulmarius, Fomes fomentarius, Agaricus subrufescens, Coprinus comatus, Hericium erinaceus, Mycoleptodonoides aitchisonii, Phellinus linteus, Schizophyllum commune,* and *Volvareilla volvacea* [42–53]. The richness of bioactive components in culinary mushrooms make them a new focus in the cosmetic industry, mushroom oil for instance, contains a variety of phenolic and polyphenolic compounds that are useful in skin lightning effects due to their free radical scavenging and antioxidant activity. According to the studies, kojic acid, a common biochemical composition in mushroom species, had been extracted and incorporated into production of creams, lotions, and serums as a remedy for age spots and discoloration [42,54]. In addition to that, cosmetic companies had been developing products using an extract from mushroom for various functions, such as *L. edodes* extract which makes the skin glow and luminous, *G. lucidum* for anti-inflammatory, collagen-boosting, and skin anti-aging effects in face mask, *C. sinensis* in skin whitening cream due to its moisturizing and melanin production-suppressing properties [42].

The biofuel industry seeks sustainable alternatives, and mushroom-derived non-food oils present a potential solution [51,55–58]. The unique lipid composition and growth characteristics of certain mushroom species offer opportunities for biofuel production. The cellulosic process is one of the most promising technologies in biofuel production an alternative to fossil fuel and support bioeconomy development. Previous research reveals that *G. lucidum* has the capability of becoming a potential candidate for biodiesel feedstock which meets the international standards of biodiesel properties via several complicated tests [15]. However, more research works are required to explore the potential of mushroom oils as a renewable resource for biofuel applications [51,55–58].

4.2. Evaluation tests of oils

Evaluating the quality of oil involves considering various factors related to its composition, characteristics, and production. The criteria for determining good-quality oil can vary depending on the type of oil (e.g., edible oil, essential oil, or non-food oil) [59]. Basically, the quality of oil is evaluated based on the following guidelines: appearance and colour, odour and flavor, fatty acid composition, processing methods, purity and contaminants, packaging and storage, certification and standards, and lab testing [59,60].

In terms of physical attributes of oil, high-quality oils should have high clarity and free from cloudiness and sediments. While the colour of the oil can vary based on the type and processing method. For example, extra virgin olive oil is often preferred with a greenish or golden hue. Furthermore, a good-quality oil should have a characteristic, pleasant aroma that is indicative of its source [59,60]. For instance, olive oil might have fruity, grassy, or peppery notes, whereas mushroom oil might have an earthy smell. The taste of oil should be consistent with the oil's variety as well as the processing method. Off-flavors, rancidity, or unusual tastes are indicators of poor quality [59–61].

From chemical perspective, the fatty acid composition is also an important criterion for evaluating whether an oil sample is of high quality or not. In edible oils, a balanced composition of saturated and unsaturated fatty acids are desirable for nutritional reasons. Besides, in certain oils, like flaxseed or fish oil, an optimal balance between omega-3 and omega-6 fatty acids is essential. However, for non-food oil, the fatty acid composition is not the main concern anymore, as long as the oil produced meets the standards of various functionality, then it is considered a good-quality oil [59–61].

Moreover, high-quality oils should be free from added substances or adulterants and contaminants such as pesticides, heavy metals, and microbial impurities. Authenticity testing can help verify the oil's purity. Apart from the physical and chemical properties, without good packaging and storage practice, oil with excellent quality will eventually oxidise and become rancid [61]. Therefore, oils should be stored in containers made of materials that do not react with the oil or allow light to penetrate. Also, exposure to heat, light, and air can degrade oil quality. Proper storage conditions, such as cool and dark environments, are essential.

When it comes to commercialization of oils, compliance of oils with industry or regional standards are important. Certifications like USDA Organic or ISO standards can indicate adherence to quality guidelines for edible oil, while oil for biofuel (biodiesel) production should meet the ASTM D6751-08 in the US and EN 14214 in the European Union. These would generally followed by chemical analysis including Laboratory tests, such as gas chromatography which can provide detailed information about the chemical composition of the oil. Sensory evaluation would be required for edible oil whereby trained sensory panels can assess the oil's aroma, flavor, and overall quality of the oils [61,62].

5. Importance and nutritional values of mushroom oil

Mushroom oil, derived from various fungal species, has emerged as a noteworthy component in the realm of functional foods and natural supplements. The exploration of mushroom oil as a nutritional powerhouse has gained momentum due to its unique composition and potential health-promoting properties. This section provides a thorough analysis of the importance and nutritional values of mushroom oil, considering its role in modern nutrition and wellness [3,16,18].

5.1. Nutritional composition of mushroom oils

Mushroom oil boasts a rich nutritional profile, comprising essential fatty acids, vitamins, and minerals. Specific nutrients found in mushroom oil, including linoleic acid, linolenic acid, ergosterol (precursor to vitamin D), tocopherols, and trace elements have been reported in recent studies. The balance of these components contribute to the oil's potential health benefits [50,63].

Essential fatty acids, in particular omega-6 and omega-3 fatty acids, are types of fatty acids in which humans are unable to synthesize on their own and required to gain through daily diet. Mushroom oil contains linoleic acid (an omega-6 fatty acid) which is crucial for maintaining the integrity of cell membranes and plays a role in skin health. Certain mushroom species contribute linolenic acid (an omega-3 fatty acid), another essential fatty acid associated with anti-inflammatory properties. Its presence in mushroom oil may contribute to a balanced omega-6 to omega-3 (ω-6/ω-3) ratio, promoting overall cardiovascular health [3,16,18].

The nutritional composition of mushroom oil makes it a noteworthy addition to the repertoire of functional foods, not only with the presence of essential fatty acids, but also vitamins and minerals. Some edible mushrooms, for example shiitake mushrooms (*Lentinula* *edodes*), oyster mushrooms (*Pleurotus ostreatus*), button mushrooms (*Agaricus bisporus*), abalone mushrooms (*Pleurotus cystidus*), enoki mushrooms (*Flammulina velutipes*), *Hericium erinaceus*, *Leccinum scabrum*, *Tuber melanosporum*, *Tuber aestivum*, *Tuber indicum*, *Agaricus blazei*, *Boletus edulis,* and *Fistulina hepatica*, can synthesize ergosterol, a precursor to vitamin D, when exposed to sunlight or ultraviolet (UV) light [64–66]. Mushroom oil may contain this precursor, offering a potential natural source of vitamin D, crucial for bone health and immune function. Mushroom oil contains tocopherols, including α-tocopherol, a form of vitamin E with antioxidant properties. Vitamin E plays a role in protecting cells from oxidative damage. Recent studies have shown the feasibility and consumer acceptance of tocopherol-rich extract from *Ganoderma lucidum, Pleurotus ostreatus, Pleurotus eryngii*, for the production of functional food [67]. Mushroom oil may also contain trace elements such as selenium, zinc, and copper depending on the species of mushroom. These minerals are essential for various physiological functions, including immune support, antioxidant defense, and enzymatic activities.

5.2. Bioactive compounds in mushroom oils

Beyond conventional nutrients, mushroom oil is a reservoir of bioactive compounds with antioxidants, anti-inflammatory, and immune-modulating properties [8,68–70]. Phenolic compounds, terpenes, and sterols are among the bioactive constituents explored in this section, highlighting their potential contributions to overall health and well-being [68–70].

Mushroom oil is rich in phenolic compounds with antioxidant properties. These compounds help neutralize free radicals, reducing oxidative stress and potentially lowering the risk of chronic diseases. Among the members of this diverse group of bioactive compounds, gallic acid a common phenolic acid found in mushrooms. It possesses antioxidant properties and has been associated with potential anti-inflammatory effects. Other phenolics such as catechins (in *Agaricus bisporus*), quercetin (in *Pleurotus ostreatus*), resorcinol (in *Grifola frondosa*), *p*-Hydroxybenzoic acid and vanillic acid were also reported in extract of certain mushroom species [71–75]. It's important to note that the phenolic composition can be influenced by factors such as the mushroom species, growing conditions, and extraction methods. The identification and quantification of specific phenolic compounds in mushroom oil often requires sophisticated analytical techniques such as high-performance liquid chromatography (HPLC) or mass spectrometry (MS) [75].

Certain mushroom species contribute terpenes, which are aromatic compounds with diverse biological activities. Terpenes in mushroom oil may have anti-inflammatory and antimicrobial effects. β-Caryophyllene which was found in various mushrooms, including oyster mushrooms (*Pleurotus* spp.), is known for its anti-inflammatory and antioxidant properties [3,8,76]. It is also an FDA-approved food additive and has potential therapeutic applications. Various mushroom species, including agarics (*Agaricus* spp.) and reishi mushrooms (*Ganoderm*a spp.) contain sesquiterpenes which are a diverse group of terpenes with potential anti-inflammatory, antiviral, and immune-modulating properties [71–75,77,78]. The presence and concentration of terpenes in mushroom oil can vary based on factors such as mushroom species, environmental conditions, and extraction methods. Terpenes contribute to the aroma, flavor, and potential health benefits of mushrooms and their oils [79,80]. It's important to note that research on the terpene composition of mushroom oil is an evolving field, and advancements in analytical techniques contribute to a deeper understanding of the bioactive compounds present in these oils [80]. Additionally, the potential health benefits associated with terpenes are an area of ongoing scientific investigation.

5.3. The impact of mushroom oil on health

The impact of mushroom oil on cardiovascular health is a focal point, considering its fatty acid composition and potential cholesterol-lowering effects [81,82]. The role of mushroom oil in maintaining lipid profiles, reducing inflammation, and supporting heart health, have been discussed recently [82]. The appropriate uptake of oil derived from mushroom biomass would bring positive health impact as if essential fatty acids were consumed in healthy proportions (1:1 or 2:1 ω-6/ω-3), the risk of getting obesity would be minimised as an unbalanced ω-6/ω-3 ratio had been reported to be associated with adipogenesis. Apart from that, the essential fatty acids participate in the formation of high-density lipoprotein (HDL) which is responsible for the transport and assimilation of fat from blood to the liver, could help prevent cardiovascular disorders such as strokes, hypertension, and hypercholesterolemia [83]. In addition, the unsaturated fatty acids especially the omega-3 fatty acids EPA and DHA could contribute to health improvements as they have the ability to modify and alter the cell membrane structure, cell protein functions, lipid mediators' production as well as the patterns of gene expression [16,83].

According to Barros, Baptista [17], the unsaturated fatty acids were likely to contribute to the *in vivo* bioactivities such as anti-inflammatory, antimutagenic and anti-hypertension effects. For example, linoleic acid isolated from Brazilian mushroom (*A. brasiliensis*) showed an anti-inflammatory effect assessed in RAW 264.7 murine macrophages cell-based assay. Linoleic acid isolated from *A. blazei* is attributed to the antimutagenic activity in Ames/Salmonella/microsome assay as reported by Barros, Baptista [17]. Besides, most unsaturated fatty acids found in mushrooms were *cis*-fatty acids. *cis*-fatty acids and *trans*-fatty acids were fatty acids with different stereochemistry, and which would lead to different health effects when consumed. A rapidly expanding literature documented the effects of *trans*-fatty acids to health-related problems in human especially the cardiovascular ones in which the *trans*-fatty acids were reported to be negatively correlated with HDL-cholesterol concentration and positively correlated with LDL-cholesterol level in plasma [17].

In brief, mushroom oil emerges as a nutritional powerhouse with multifaceted benefits for human health. Its unique composition, encompassing essential nutrients and bioactive compounds, positions it as a valuable addition to a balanced diet. As ongoing research continues to unravel the full spectrum of health-promoting properties, mushroom oil stands at the forefront of functional foods, presenting opportunities for dietary enrichment and wellness promotion [8].

6. Chemical structures of fatty acid derived from mushroom biomass

This section unveils the intricate processes underlying the production of essential lipid components within the fungal organisms. Fatty acids serve as fundamental building blocks, contributing to the structural integrity of cell membranes and playing pivotal roles in energy storage and cellular signaling. This comprehensive exploration delves into the enzymatic pathways involved in the biosynthesis of fatty acids, unravelling the molecular intricacies that govern the formation of these crucial molecules in mushroom cells. Additionally, this section examines the diverse chemical structures of fatty acids found in mushrooms, shedding light on variations in chain length, saturation, and modifications that contribute to the functional diversity of these lipids. This in-depth analysis aims to enhance the understanding of the biosynthetic machinery within mushrooms, with potential implications for applications ranging from nutritional science to biotechnological advancements.

6.1. *Biosynthetic pathway of fatty acids in mushroom*

The biosynthesis of fatty acids in mushrooms, as in other organisms, involves a series of enzymatic reactions that occur in various cellular compartments, primarily within the fungal cell's cytoplasm and endoplasmic reticulum. The process is essential for the production of lipids, including fatty acids, which serve as structural components of cell membranes and play crucial roles in energy storage and signaling [84,85].

Fatty acid biosynthesis starts with the conversion of acetyl-CoA, a key metabolite derived from various cellular processes, acting as precursors of fatty acids, into malonyl-CoA. This reaction is catalyzed by the enzyme acetyl-CoA carboxylase (ACC). This carboxylation reaction is the committed step in fatty acid biosynthesis and is crucial for providing the two-carbon building blocks needed for fatty acid elongation [86]. The process is then followed by the synthesis of fatty acids involving a cyclic process called fatty acid synthase (FAS) or type I polyketide synthase system. In fungi, including mushrooms, the FAS system is multifunctional and consists of several enzymatic domains within a single polypeptide chain. The fatty acid chain elongation occurs through the repetitive addition of two-carbon units from malonyl-CoA to yield a growing fatty acid chain. Each cycle of the FAS system includes reactions such as condensation, reduction, dehydration, and rehydration, leading to the extension of the fatty acid chain [86,87]. In some cases, the synthesized fatty acids may undergo desaturation, where double bonds are introduced into the carbon chain [86–88]. Desaturases are enzymes responsible for this process [86–88]. Additionally, modifications such as acetylation or other enzymatic transformations may occur, leading to the production of diverse fatty acid species with different properties among mushroom species [86,87]. The related reactions and enzymes are shown in Fig. 1.

The synthesis of specialized fatty acids (FAs) in microorganisms is intricately linked to polyketide synthases (PKS). PKS serves as a sophisticated molecular apparatus responsible for the synthesis of polyketides, which are natural products arising from secondary metabolism and share similarities with fatty acids [85,87,89,90]. The production of docosahexaenoic acid (DHA) in *Thraustochytrium*, *Schizochytrium limacinum*, and *Aurantiochytrium* sp. is believed to involve the PKS pathway. This pathway initiates with successive condensation reactions of precursors catalyzed by PKS, forming a diverse array of polyketides. Subsequent modification reactions,

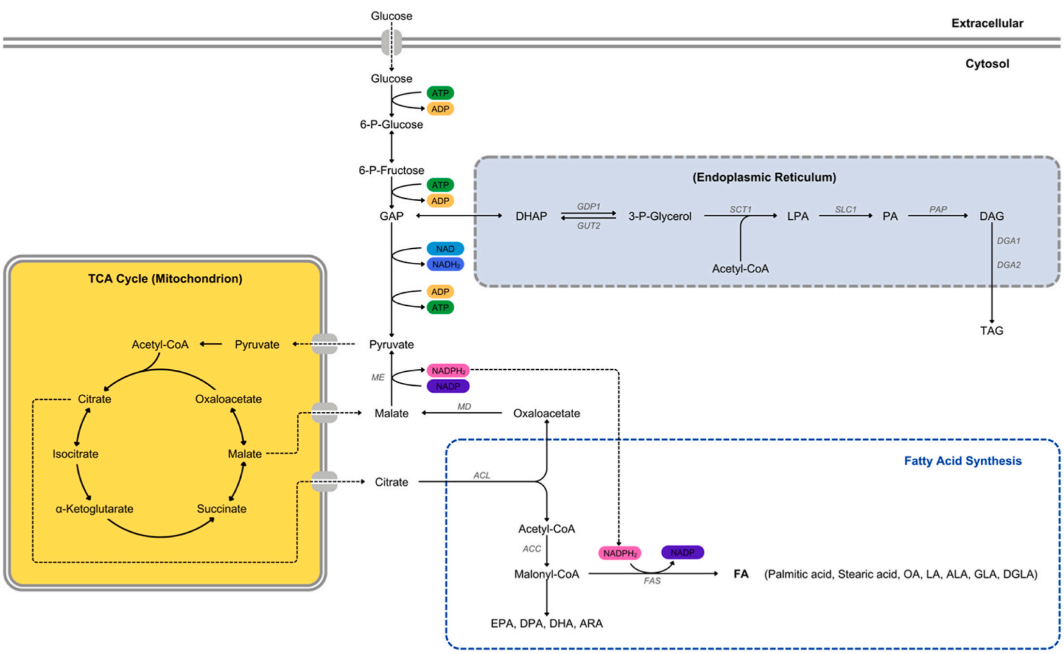


Fig. 1. Biosynthetic pathways of triacylglycerols (TAGs) and fatty acids (FAs) in microbial cells.

including methylation, redox reactions, glycosylation, and hydroxylation, yield numerous complex compounds [85,87,91]. Structurally, PKS can be categorized into three types: modular (type I), repetitive (type II), and chalcone (type III). Fungal PKS, predominantly type I, comprises large multifunctional proteins encoded by a single gene, featuring multiple similar modules with some domains reused during compound synthesis [87,90]. Type I exhibits a multidomain architecture with active sites distributed across large modules, while type II consists of monofunctional enzymes with catalytic sites separated on different proteins [87,92]. Type III polyketide synthases (PKSs) produce secondary metabolites with diverse biological activities, including antimicrobials [87,93,94]. Unlike types I and II, type III PKSs, dimers of ketone synthases, undergo a series of reactions, including primer substrate initiation, decarboxylation condensation of extended substrates, ring closure of growing polyketide chains, aromatization, and produce a variety of biologically active aromatic compounds [95]. The PKS pathway of select species is illustrated in Fig. 2 [87].

6.2. Chemical structures of fatty acids in mushroom oil

Fatty acids are integral components of lipids and play crucial roles in various physiological processes, making them essential for human health. Mushroom oil, a relatively understudied yet promising source of fatty acids, offers a unique array of chemical structures that contribute to the chemical diversity of fatty acids in mushroom oil, as shown in Table 4.

The nomenclature of fatty acids could be summarized as [number of carbon atoms in the aliphatic chain: the number of double bonds]. According to the International Union of Pure and Applied Chemistry (IUPAC), there are two possible ways in numbering the carbon atoms: (i) the carbon of carboxyl group will be given number one whereas the positions of the double bonds are specified relatived to carbon one by numbers superscripted to Δ (delta); (ii) or the carbon located farthest from the carboxyl group, that is the carbon of the aliphatic group, known as ω-carbon (omega), receiving the numbering of one. Conventionally, PUFAs, which are essential fatty acids, are better known by their omega nomenclature, for example: omega-3 (ω-3), with a double bond between the third and fourth carbon atoms, omega-6 (ω-6), between the sixth and seventh carbon atoms, omega-9 (ω-9) and, between the nineth and tenth carbon atoms [16,104].

This section delves into the chemical structures of fatty acids present in mushroom oil, from the saturated to unsaturated, long-chain to polyunsaturated fatty acids, the intricate molecular profiles contribute to the nutritional richness of mushroom oil. The chemical structure of a saturated fatty acid in mushrooms, like in many other biological systems, is characterized by a straight carbon chain with only a single bond between adjacent carbon atoms, forming the foundational part of mushroom oil. Common SFAs found in mushroom oil include palmitic acid (C16:0) and stearic acid (C18:0) [16–24,105]. These SFAs contribute to the stability and structural integrity of the oil, influencing its physical properties. Palmitic acid is a major component of many dietary fats and oils, and its presence in mushrooms contributes to the overall lipid composition of these fungi [16–24,105]. Understanding the chemical structure of saturated fatty acids like palmitic acid is essential for studying their nutritional significance and potential health effects. Stearic acid is a saturated fatty acid that belongs to the group of long-chain fatty acids. It is a crucial component of various natural fats and oils, including those derived from animals and plants. The chemical formula of stearic acid is $C_{18}H_{36}O_2$ or $CH_3(CH_2)_{16}COOH$, indicating that it has 18 carbon atoms in its hydrocarbon chain. Understanding the properties and roles of palmitic acid and stearic acid are crucial for assessing their nutritional impact and considering dietary recommendations. While they are naturally occurring components of many foods, maintaining a balanced and diverse diet is key to overall health and well-being. While excess consumption of

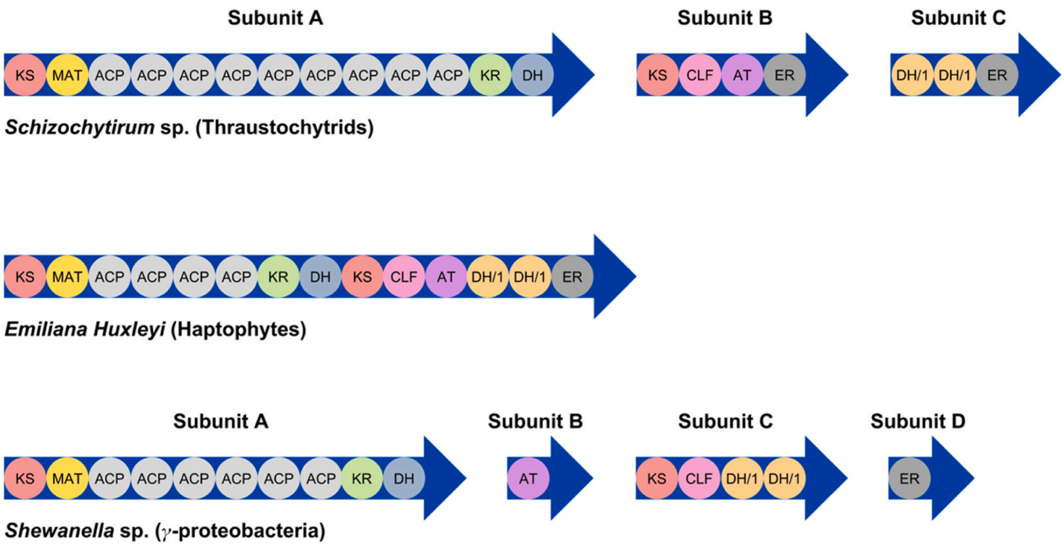
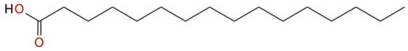
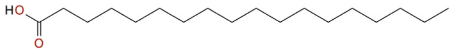
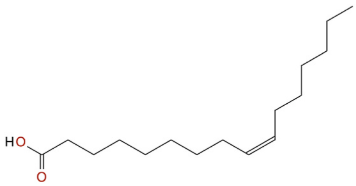
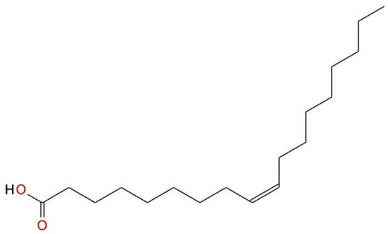
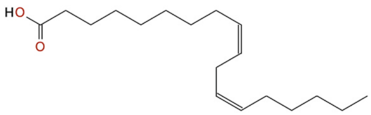
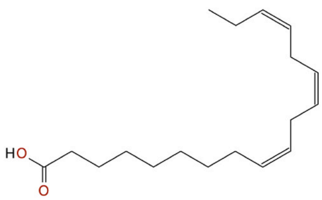


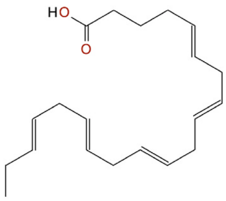
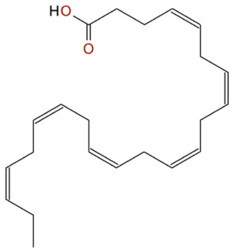
Fig. 2. Examples of PUFA synthase organisation in thraustochytrids, haptophytes and γ-proteobacteria. KS, β-ketoacyl synthase; MAT, malonyl-CoA: ACP transacylase; ACP, acyl-carrier protein; KR, β-ketoreductase; DH, dehydratase; CLF, chain length factor; AT, acyl transferase; ER, enoyl-reductase; DH/I, dehydratase/isomerase.

Table 4
The chemical structure of common fatty acid derived from the mushroom biomass.

Class	Name	Chemical and Molecular formula	References
SFA[a]	C16:0 Palmitic acid Hexadecanoic acid	 $C_{16}H_{32}O_2$	Agostoni, Moreno and Shamir [96]
SFA	C18:0 Strearic acid Octadecanoic acid	 $C_{18}H_{36}O_2$	Sagiri, Singh [97]
MUFA[b]	C16:1, $\Delta^{9\ (\omega-7)}$ Palmitoleic acid (9*Z*)-hexadec-9-enoic acid	 $C_{16}H_{30}O_2$	Frigolet and Gutiérrez-Aguilar [98]
MUFA	C18:1, $\Delta^{9\ (\omega-9)}$ Oleic acid (9*Z*)-octadec-9-en [17]oic acid	 $C_{18}H_{34}O_2$	Tutunchi, Ostadrahimi and Saghafi-Asl [99]
PUFA[c]	C18:2, $\Delta^{9,12\ (\omega-6)}$ Linoleic acid (9*Z*,12*Z*)-octadeca-9,12-dienoic acid	 $C_{18}H_{32}O_2$	Jandacek [100]
PUFA	C18:3, $\Delta^{9,12,15\ (\omega-3)}$ Linolenic acid (9*Z*,12*Z*,15*Z*)-octadeca-9,12,15-trienoic acid	 $C_{18}H_{30}O_2$ $C_{18}H_{30}O_2$	Yuan, Xie [101]

(*continued on next page*)

Table 4 (*continued*)

Class	Name	Chemical and Molecular formula	References
PUFA	C20:5, $\Delta^{5,8,11,14,17\ (\omega-3)}$ Eicosapentaenoic acid (EPA) (5*Z*,8*Z*,11*Z*,14*Z*,17*Z*)-eicosa-5,8,11,14,17-pentaenoic acid	 $C_{20}H_{30}O_2$	Nelson and Raskin [102]
PUFA	C22:6, $\Delta^{4,7,10,13,16,19\ (\omega-3)}$ Docosahexaenoic acid (DHA) (4*Z*,7*Z*,10*Z*,13*Z*,16*Z*,19*Z*)-docosa-4,7,10,13,16,19-hexaenoic acid	 $C_{22}H_{32}O_2$	Calder [103]

[a] Saturated fatty acid.
[b] Mono-unsaturated fatty acid.
[c] Polyunsaturated fatty acid.

saturated fats is generally advised against due to potential health risks, stearic acid, when consumed in moderation, is considered to have a more neutral impact on cardiovascular health compared to certain other saturated fatty acids [16–24,105].

Palmitoleic acid and oleic acid, essential mono-unsaturated fatty acids (MUFAs), are prevalent in various dietary sources, with mushrooms, particularly specific species, contributing significantly to their presence. Palmitoleic acid, characterized as an omega-7 fatty acid with a 16-carbon chain ($CH_3(CH_2)_5CH{=}CH(CH_2)_7COOH$), is found in mushrooms such as shiitake (*Lentinula edodes*). Recognized for its anti-inflammatory properties, palmitoleic acid offers potential cardiovascular benefits by reducing LDL cholesterol levels. Moreover, it is valued in skincare for its moisturizing and rejuvenating effects. Oleic acid, classified as an omega-9 mono-unsaturated fatty acid with an 18-carbon chain ($CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$), is a common component of mushrooms like oyster mushrooms (*Pleurotus* spp.). Abundant in olive oil, oleic acid is associated with cardiovascular health, lowering LDL cholesterol and elevating HDL cholesterol levels. Its anti-inflammatory attributes further contribute to potential protection against chronic inflammatory conditions. Functioning as a major component of cell membranes, oleic acid plays a crucial role in maintaining cellular structure and function [16–24,105].

Both palmitoleic acid and oleic acid are integral to a balanced diet, and mushrooms, along with nuts, seeds, and olive oil, serve as natural sources of these healthy MIFAs. Incorporating these foods enhances overall nutritional well-being. Mushrooms containing these fatty acids can be seamlessly integrated into various culinary dishes, enhancing both flavor and nutritional content. Additionally, the use of olive oil, rich in oleic acid, in cooking and as a salad dressing provides a delectable means of obtaining these beneficial fatty acids. Ensuring a diverse range of foods, including mushrooms, in the diet ensures a balanced intake of essential fatty acids. Despite not being produced in the human body, incorporating mushroom-derived sources adds nutritional variety and potential health benefits to the diet. Embracing a diverse and balanced approach to dietary choices can contribute to overall well-being and health [16–24,105,106].

Linoleic Acid (LA) is an essential omega-6 polyunsaturated fatty acid crucial for human health. With a chemical structure represented as $CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$, it consists of 18 carbon atoms and two double bonds [16–24,100,105]. Found in some mushrooms, especially those exposed to sunlight, linoleic acid plays a pivotal role in synthesizing other fatty acids and contributes to skin health, inflammation regulation, and cell structure maintenance [16–24,82,105]. Linolenic Acid (ALA) is an essential omega-3 polyunsaturated fatty acid, vital for heart health and inflammation reduction [82]. With a chemical structure denoted as $CH_3CH_2CH{=}CHCH_2CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$, it comprises 18 carbon atoms and three double bonds. Mushrooms are recognized for containing linolenic acid, contributing to their overall lipid profile. Serving as a precursor to other omega-3 fatty acids, including EPA and DHA, linolenic acid plays a crucial role in supporting cardiovascular health [16–24,105].

Mushrooms offer not only these well-known fatty acids but also special fatty acids with distinct benefits. Ergosterol fatty acids are synthesized by mushrooms when exposed to sunlight, contributing to the potential as a natural source of vitamin D [107,108]. Ergosterol, structurally akin to cholesterol, undergoes variations in side chains in ergosterol fatty acids, impacting bone health and immune function. Certain mushroom species may contain Conjugated Linoleic Acid (CLA), a group of geometric and positional isomers of linoleic acid [109,110]. CLA is acknowledged for its potential health benefits, including anti-inflammatory and anti-cancer properties. The diverse isomers of CLA, with distinct double-bond configurations, contribute to its various biological activities [109]. Understanding the chemical structures of these fatty acids is crucial for comprehending their roles in nutrition and potential health benefits, including anti-inflammatory and anti-cancer properties. Mushrooms, with their unique fatty acid composition, contribute to a varied and nutritious diet, showcasing their potential beyond culinary appeal. The inclusion of these fatty acids adds to the nutritional diversity that mushrooms offer, emphasizing their role in promoting overall well-being [111,112].

7. Economical aspects and future Business commercialization of mushroom-biomass oil

Fungi is a natural treasure of our planet with its excellent adaptation to the environment as well as the richness in bioactive compounds content. Despite its ability to convert organic matter into a wide range of high-value products, it also has great potential in tackling urgent challenges before all humans. The advancement of fungal biotechnology will potentially be shifting our society from a non-renewable fossil-based economy into a sustainable resource-saving circular bioeconomy [57]. Several studies have shown that the feasibility of extracting oil from mushroom biomass and the applications of the extracts in different industries. Besides the pharmaceutical and nutritional sectors, one of the most concerned fields for mushroom-based oil is integrated as feedstock in the production of biofuel [51,55–58].

When mentioning about the fungi-based biorefinery model for the bioenergy industry, the economic value of the final product, which is the biofuel (e.g., biodiesel, bioethanol, etc.), is always being emphasized as the measure of its opportunity for being commercially marketed and applied for daily use [58]. And certainly, fungal-based oil alone is less likely to make a significant impact on the economy as there are other alternatives available which could have lower cost and higher yield. Therefore, the concept of circular economy in mushroom-biomass oil industry is brought into the sight not only for the development of sustainable energy source, but also to stimulate the economy as well as to reduce the waste and cost during the production [51,55].

To achieve the ultimate goal of sustainable bioeconomy operating in a circular manner, all the wastes or co-products produced from the upstream and downstream bioprocesses should be reusable or recycled and modified into value-added products [56]. In the production of mushroom-biomass oil, for instance, the mushroom biomass would first be cultivated and undergo mass production, followed by extraction of biomass and lipid. These processes will produce a huge amount of waste once it is produced in an industrial scale. Therefore, research and studies on recycling the culture media in fungiculture and the possible approaches for reducing the waste generation along the production of mushroom-biomass were conducted, targeting to achieve a circular economy [51,55–58].

The culture media of mushroom cultivation through both solid-state fermentation (SSF) as well as submerged liquid fermentation (SLF) were reported to show their capabilities to be integrated into agriculture systems as fertilizers which might require some alterations in the media formulations. This is a sustainable approach for managing the agro-industrial residue by transforming them into useful products which can potentially improve the crop yield in olericulture and agriculture, thus enhancing food security [13,55].

Conventionally, if mushroom-biomass oil is the product of interest, the biomass will be the residue during the lipid extraction process and will normally be discarded as biochemical waste. However, the mushroom biomass is a co-product with important biotechnological potential which is suitable for connecting agricultural, medicinal, and pharmaceutical systems within the percepts of the circular bioeconomy [51,55–58]. In the case of the production of mushroom-biomass oil from common culinary mushroom, the left over mushroom biomass after lipid extraction can be used as fertilizer for agricultural purposes or being used as raw material for manufacturing of mushroom products which had been commercialized. If medicinal mushroom is being used as the feedstock for producing mushroom-biomass oil, the biomass residue could potentially be incorporated as ingredients of mushroom-based supplements with high medicinal value [113].

8. Feasibility towards SDG 2 oil for consumption and SDG 7 oil for energy

In 2015, the United Nations adopted Sustainable Development Goals (SDGs) as a blueprint for all countries to promote prosperity while protecting the mother planet with a better and more sustainable future for all. Among all 17 SGDs, the SDG 2 (zero hunger) and SDG 7 (affordable and clean energy), are relatable to the current study.

Preserving food and food production, enhancing food security is the focus of SDG 2. However, population growth, climate change, and food shortage have led to increased demand for alternate sources of lipids to meet the global food and energy needs. Oleaginous basidiomycetes are good resources for lipid production. Fungal-based oil produced from biomass or fruiting body of basidiomycetes has high nutritional value due to the richness of bioactive compounds and polysaccharides reported in several mushroom species [16–18]. The secondary metabolites extracted from the intracellular content of different fungal species have been reported to possess antibacterial, antifungal, anticancer and antiviral properties which had been proven to prolong the shelf-life of food with the extract integrated into the food product during the production process [7,8]. Thus, the mushroom-biomass oil that is rich in bioactivity could potentially become an alternative to replace the commercially available lipid in the formulation in achieving the goal of SDG 2 [114–119].

Furthermore, oil extracted from mushroom have been reported to have significant level of Docosahexaenoic acid (DHA), which is a main constituent found in fish oil, and the selling point of the fish oil products marketed commercially. Therefore, mushroom-biomass oil could be an alternative for consumers as DHA supplements and even act as an additive to fish feed for aquaculture industry, playing an important role in preserving the ecosystem, by preventing overfishing and promoting aquaculture [16,120]. Yet, lowering the risk of food crisis with higher food yield not only in aquaculture industry, but also in agricultural sector. Recent studies have shown that oil extracted from mushroom biomass which is highly nutritional can be incorporated in our daily meals replacing the plant-based edible oil and cooking oil. This will profoundly reduce the demand for plant-based feedstock for edible oil production as fungal-based oil is an excellent alternative which will aid in the issue of food security because most of the current commercially available cooking oil are made from crop plants, which is important food and energy source for human being. Thus, mushroom-biomass oil could potentially be used to replace plant-based oil and preserve food security to achieve the goal of SDG 2.

The oil extracted from mushroom biomass does not only meet the criteria in achieving the UN SDG 2, it also can potentially be used for the access to affordable, reliable, sustainable, and modern energy which is the focus of SDG 7. This form of bioenergy had been the main concern to play its importance as part of energy mix. For decades, the commercialization of bioenergy production from oilseeds and plant-based feedstocks had led to the creation of agricultural and forestry jobs, as well as to higher wages and more diversified income streams for landlords [121]. The technically matured and well-developed upstream and downstream production of biofuels had been established; however, this could lead to a higher global food price, and to competition between biofuels and food crops over the scarce agricultural land, water, and energy for biofuels production. These would result as an opposition to the SDG 2 as proposed to achieve zero hunger, as the poor would have difficulties with accessing to affordable food due to increasing food price yet deteriorating the alarming status of food security because of the competition between production of biofuels and food crops [121].

Although, attempts for reducing the reliance on plant-based feedstock in bioenergy production, such as fuels production from domestic wastes, which do not compete with food production, had being reported to be a feasible alternative way for bioenergy production, nonetheless, the transportation of waste residues and operation of the processing plants can be energy-intensive. Therefore, studies on an alternative cost-effective, energy-efficient, and high-yielding biofuel production had been conducted to replace fossil fuels in the road to achieving SDG 7 [121,122]. Oleaginous fungi had recently been suggested as bio-factories and alternative lipid producer to vegetable oil for a more sustainable biofuel industry. Biodiesel produced from fungal materials are sustainable, more efficient than biodiesel produced by oilseeds, and have similar production costs. Furthermore, with the aid of advanced biotechnological tools, such as genetic engineering, improvements could be achieved by developing fungal strains that convert low-cost substrates, grow rapidly, and produce larger quantities of neutral lipid. Improved harvesting and dewatering technologies could also help in enhancing the yield of biodiesel from biomass of fungi.

Mushroom had been suggested as the feedstock for biodiesel production as some of the mushroom species have the ability to accumulate oils under some special cultivation conditions, with the considerations of different prospects in terms of lipid yield, lipid coefficient, and lipid volumetric productivity. Further optimization and improvement in the abilities of mushroom for higher growth rate, larger biomass, higher lipid yield and higher lipid content is favorable, despite having cheap carbon sources or oil accumulation, as this is very important for such oils applied to biodiesel production in the future. Alternative lipid source for bioenergy production is in a pressing demand as the depletion of fossil-based fuels will be accelerated along with the growing global population. Biofuels, including biodiesel and bioethanol would undoubtedly be a perfect solution to energy crisis, yet the challenges for lipid source for biofuel production had arisen as reported by some researchers, biodiesel produced from two major raw materials, soybean, and

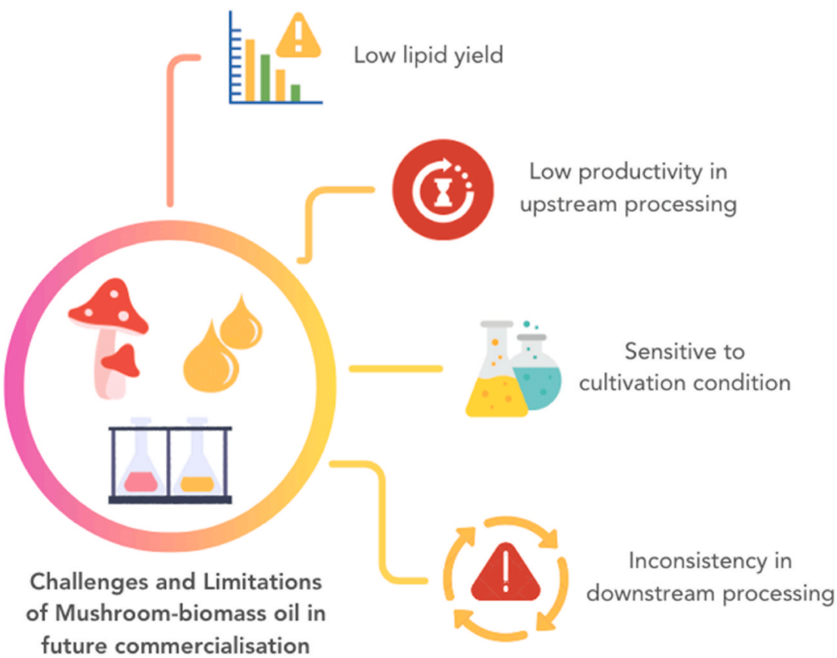


Fig. 3. Overview of challenges and limitations of mushroom-biomass oil in future commercialization from upstream to downstream processes.

sunflower, was energetically unfavorable due to low lipid yield of the crops (energy loss of 32 % for soybean and 118 % for sunflower) [120,122–126].

General speaking, mushroom-biomass oil might become one of potential feedstock for biodiesel production in the future since it has the following advantages: renewability, fast growth rate, and not taking arable land. Future modifications through genetic engineering and metabolic engineering have much potential for the performance improvement of mushroom in lipid production.

9. Challenges, limitations and future works

Mushrooms were regarded as a popular healthy food which had low lipid content and high nutritional values, suitable to lower the risk of cardiovascular diseases to the consumers. However, problems arose when it comes to the production and extraction of lipid from mushroom biomass where the lipid yield is relatively low. Based on the literature, the yield of the lipid extracted from the mushroom biomass varied depending on the fungal species, extraction techniques, treatment, solvent used and extraction time, which were reported to have a range of 0.003 %–0.15 %. In other words, for 100 g of dried biomass, the resulting mushroom oil obtained would only be 0.003 g–0.15 g [1–3,34,40]. Therefore, when a research work that requires a relatively large quantity of mushroom-based lipid is to be done, the cultivation and growth conditions of the selected fungal strain need to be optimized in order to obtain the maximum level of mushroom biomass with the least resources available. Challenges and limitations of mushroom-biomass oil is depicted in Fig. 3.

Since the production of lipid from mushroom biomass is limited by its lipid content, hence the most possible solution for this challenge is to increase and optimize the production of biomass of fungal strain. The optimization could be done in several ways including the growth, fermentation techniques, and recovery procedures. In the cultivation of mushroom biomass, one of the factors that were directly correlated with the growth of fungi was the nutrients supplied to the fungal strain. The carbon source, nitrogen source, minerals, macronutrients and micronutrients required varied with the fungal strains. Furthermore, the quantity of the supplemented nutrients also played a vital role in affecting the growth of the mushroom biomass as some strains might require different C:N ratio in the nutritional profile. Hence, the choices of chemicals were crucial in optimizing the growth rate of mushroom biomass in order to obtain the highest yield of biomass in a single batch of fermentation.

Apart from the nutritional perspective, the physical fermentation conditions were also important in influencing the production of mushroom biomass. For instance, the fermentation temperature needs to be kept constant at optimum (30–35 °C) for maximum biomass growth as well as to achieve most ideal yield for the products of interest. Temperature is a crucial parameter in the biological components of fungi, especially the proteins and enzymes are extremely sensitive to the change in temperature, therefore an optimal culture temperature is the key factor in achieving high biomass production. Besides, other parameters such as the agitation rate, dissolved oxygen, aeration rate, and pH were reported to significantly influence the biomass production during the fermentation process. All these parameters will result in changes in the metabolic rate of fungal cells, thus affecting the growth rate and mycelial biomass pellet size. Hence, more studies and research on the optimum conditions of mushroom biomass fermentation of different fungal strains would be required for upscaling of biomass production in mushroom.

The optimization of the production of mushroom oil from fungal biomass could help in stimulating the economy of the nation thus contributing to the nation's gross domestic products (GDP) as if the production is conducted in industrial scale, the mushroom-derived lipid are able to be used as raw material for the manufacturing of nutraceutical, pharmaceutical and cosmeceutical products or even act as feedstock for the production of bio-oil products such as bio-lubricants, biofuels and so on. If possible, these fungal-based oil could even be processed and used as alternatives to vegetable oils. If so, this could help in solving the problem of food security as the current production of edible oil, lubricant and fuels are plant-based which will compete with the food security. The advancement in producing lipid products from fungal feedstock will be an ultimate solution to these challenges.

10. Conclusions

In this comprehensive exploration of mushroom-biomass oil, it becomes evident that despite mushrooms generally have low lipid content, they are rich in essential fatty acids and bioactive compounds that confer numerous health benefits. The fatty acid composition, varies across mushroom species, is characterized by a balance of saturated (SFAs), mono-unsaturated (MUFAs), and polyunsaturated fatty acids (PUFAs), with linoleic acid and oleic acid playing pivotal roles. The burgeoning field of mushroom essential oils offers unique chemical compositions, influenced by extraction methods and fungal species. These oils, with their diverse volatile compounds, open doors to applications in health, beauty, and gastronomy. The potential of mushroom essential oils is reinforced by ongoing research delving into their extraction methods, chemical compositions, and therapeutic properties.

In addition to that, the economic aspects of mushroom-biomass oil are explored, focusing on the transition towards a circular bioeconomy. The integration of sustainability, waste reduction, and economic stimulation forms the basis for the commercialization of mushroom-biomass oil, which extends beyond traditional applications to biofuel production and agricultural fertilization. Further, the feasibility of mushroom-biomass oil aligns with the United Nations Sustainable Development Goals, particularly SDG 2 (zero hunger) and SDG 7 (affordable and clean energy). The oil's nutritional richness positions it as an alternative for achieving zero hunger by enhancing food security. Simultaneously, it serves as a sustainable bioenergy source, contributing to the global pursuit of affordable and clean energy. However, challenges persist, notably the low lipid yield, necessitating ongoing research into optimizing fungal biomass production. The economic implications are vast, with mushroom-derived lipids offering raw materials for diverse industries, from pharmaceuticals to biofuels.

In this review, the nutritional composition of mushroom oils is a focal point, emphasizing their richness in essential fatty acids, bioactive compounds, and trace elements. The bioactive compounds in these oils, including phenolic compounds and terpenes, contribute to antioxidant and anti-inflammatory effects, promoting overall health and wellness. The understanding of the biosynthetic processes of fatty acids within fungal organisms which elucidate the intricate processes involved, could help to enhance our appreciation for the nutritional significance of mushroom-biomass oil and its potential to contribute to a balanced diet.

In conclusion, the multifaceted nature of mushroom-biomass oil positions it as a valuable resource, not only in traditional food applications but also in emerging industries such as cosmetics, pharmaceuticals, and biofuels. Ongoing research and exploration are essential to fully harness the benefits of mushroom-biomass oil and integrate it into diverse sectors, shaping a sustainable and health-conscious future.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:ZUL ILHAM reports financial support was provided by Ministry of Higher Education (MOHE) Malaysia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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